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Bone Mineral Density in Top Level Male Athletes of Different Sports

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The purpose of this study was to determine the influence of muscle strength, training-specific and anthropometric parameters on bone mineral density (BMD) in male top athletes of different sports in comparison to untrained controls. BMD was measured by dual energy X-ray absorptiometry in 173 males, aged 18 to 31 years. Of these, 104 were athletes (runners, n = 21; cyclists, n = 12; triathletes, n = 18), heavy athletes (HA, judo and wrestling, n = 28), and team sport athletes (TS, handball, soccer, basketball, volleyball, n = 25); 44 were unspecifically trained sport students (STU); and 25 were untrained controls (UT). Sport- and group-specific differences were found in anthropometric but not strength parameters. Marked sport- and group-specific differences were found for BMD at lumbar spine (LSP) and the femoral sites (FEM). Group-specific effects on BMD were clearest when calculating percentual differences between BMD of athletes and UT: In group I (HA, TS, and STU), BMD at LSP and FEM were significantly ($p < .01$) higher compared to UT; in group II (R and TRI), BMD at FEM but not at LSP was higher compared to UT ($p < .01$); and in group III (C), no BMD value was significantly different from UT. Multiple regression analysis revealed lean body mass to be the strongest predictor for BMD at LSP and FEM. We conclude that mechanical loads have strong effects on bone adaptation. Sport-specific and body region-specific effects have to be taken into account for evaluation of osteogenic effects of exercise. Particularly dynamic sports with short, high, and multidimensional loads have the strongest effects on bone formation, independent of training quantity.

Key Words: bone mineral content, physical exercise, sports-specific mechanical strain, muscle strength, body composition

Key Points:

- Athletes who move their whole body with high accelerations and in multidimensional directions have high positive osteogenic effects at both sites, the lumbar spine and the femoral regions.
- If athletes primarily use their lower extremities in a dynamic way for moving forward and whole body has to be carried by lower extremities, as in running, positive osteogenic effects will primarily occur at the lower extremities.
- Demands in sports like cycling—where only part of the body mass (lower extremities)

is used dynamically and cyclically without high accelerations and impacts, and most of the rest of the body is carried passively sitting on the saddle and being fixed by the arms—are too low to induce a remarkable osteogenic stimulation at the axial skeleton and the proximal femur.
• Mechanically induced adaptations at the proximal femur occur especially at the site with the highest risk for fractures, the WARD's triangle, leading to higher BMD values and thereby, probably, higher stability.
• Osteogenic effects are not sport-specific but load- and body region-specific.
• Height of strain is the most important factor for bone formation in male humans.
• Training regimes with high volume but low intensities do not or only slightly induce osteogenic effects, while a variable training protocol with short but high forces will have the highest positive stimulatory effects on bone formation.

1 Introduction

Both men and women are at risk for osteoporotic fractures. As osteoporosis is more common in females, most exercise-related research has focused on reducing the risk of osteoporotic fractures in women (2). However, as osteoporosis is a growing problem also in males (23), more information is needed about factors influencing bone mass in this gender. Studies in males have reported that athletic training leads to an increase of bone mineral density (BMD), particularly in the highly stressed parts of the skeleton, such as in the playing arm of tennis players (9). It is not known whether these adaptations are induced by muscle pull or by mechanical or other factors.

Experiments with animals revealed that new bone formation depends less on duration of mechanical stress and more on its magnitude, rate, and distribution—especially strains of high rate and magnitude and of abnormal distribution stimulated new bone formation (17, 24). Thus, it can be hypothesized that athletic activities with dynamic and impact loading patterns with variable stimuli show the strongest osteogenic effects (4). However, advantages of one exercise program over another are still unclear. Human exercise studies have generated mixed results. Only a few studies are available on the osteogenic effects of long-term athletic training on different skeletal sites in male athletes of different sports (6, 9). Furthermore, only a few results have been published on the effects of mechanically complex team sports with variable stimuli on BMD (3, 18, 28). Therefore, many open questions remain concerning the specific in vivo effects of different mechanical loads on bone in males.

The influences of anthropometric characteristics with their more or less global effects on bone have been studied in some investigations. The results of these studies most often revealed a positive influence of total body weight, body mass index (BMI), lean body mass (LBM), body fat, and height on BMD, with, however, a large variation in correlation coefficients (5, 6, 21, 29). The correlations between anthropometric parameters and BMD might partly be explained by their mechanical effects on bone (1, 14). Body weight, for instance, provides resistance that muscles must overcome for work and play (8). It remains unclear, however, whether BMD is determined by body weight per se or by single components of body composition.

The main aims of the present investigation are: (a) to determine BMD at different sites of the skeleton in top athletes of different sports and to compare these values with BMD of untrained controls in the same age group; and (b) to evaluate the influences of muscle strength, training-specific and anthropometric parameters, and especially the influence of total body muscle mass on BMD.

2 Methods

Subjects

One hundred and four male top level athletes, 44 unspecifically trained male sport students (STU), and 25 untrained male controls (UT) aged between 18 and 31 years gave their written, informed consent to participate in this study. The study design as well as possible risks had been explained in detail to each participant. (The study was approved by the Bundesamt für Strahlenschutz [Munich] for studies dealing with radiation exposure on humans and by the ethics committee of the German Sport University, Cologne.) Subjects were recruited from the German Sport University, Cologne, the University of Cologne, local as well as regional high level sport clubs, the regional Olympic center, and sport associations. The athletes were divided into 5 sport groups: running (R, $n = 21$), cycling (C, $n = 12$), triathlon (TRI, $n = 18$), heavy athletics (judo and wrestling; HA, $n = 28$), and ball team sport (handball, soccer, basketball, volleyball; TS, $n = 25$). Training amount of UT was less than 2 hours per week. All athletes had been training 6–8 times per week for at least 2 years in their specific sport. They were on national and, partly, international performance levels. STU had regular sport courses of many different types during their study at the German Sport University.

Protocol

All tests were conducted at the German Sport University, Cologne. After a medical investigation, a standardized questionnaire assessing information regarding the family history or personal history of bone fractures, exercise training history, dietary preferences, weekly intake of certain food, and supplementation of vitamins and minerals was applied to exclude risk factors or medications that might interfere with bone metabolism. Intake of drugs like anabolic steroidal hormones or growth hormones was an exclusion criterion. Following this examination, venous blood and urinary samples were taken for biochemical analysis in order to exclude diseases that might interfere with bone metabolism. Thereafter, anthropometric characteristics and grip strength values were measured. BMD was measured in a mobile unit (Osteomobil) that was placed on the premises of the German Sport University, Cologne for a period of 8 weeks.

Measurements of maximal isometric strength of back extension, and hip abduction and adduction were carried out in the track and field hall of the University on separate days.

Procedures

Height was measured to the nearest 0.1 cm on a wall-mounted tape measure, and weight was determined on a digital scale after an overnight fast. The dominant arm and leg were determined by questionnaire. Waist and hip circumferences as well as span of arms were measured with a tape measure, and hip/waist ratio was calculated. Body composition was measured by means of

10-point skinfold measurement (19) using a modified Harpenden-Caliper (Jone, British Indicators, UK). Percentual body fat was calculated with the following formula: Fat (%) = $22.32 \cdot (\log\Sigma x_i) - 29.10$, with x_i being the thickness in millimeters of the 10 respective points. Fat mass was calculated from total weight, and lean body mass (LBM) resulted from subtracting fat mass from weight.

Grip strength of the right and left hand while compressing a ball was determined with a vigorimeter (Martin, Tuttlingen, Germany). The obtained pressure inside the pressed ball was measured with a connected manometer. Optimal adaptation to different hand sizes was achieved by using different sizes of pressure balls. All subjects were familiarized with the testing procedures before testing. The best out of three trials with each hand was taken as maximal strength of the respective hand. Grip strength was measured in bar.

Maximal isometric back strength and maximal isometric strength of hip adduction and hip abduction were measured in a subgroup of 60 subjects (UT: $n = 6$, STU: $n = 24$, R: $n = 7$, C: $n = 5$, TRI: $n = 6$, HA: $n = 12$) with instruments from David Fitness & Medical Ltd. (Vaanta, Finland). Accuracy and test-retest reliability of these instruments have been proven before (7). Subjects were familiarized with the David instruments and strength testing procedures before testing. Back extension strength was measured using David 110 Back Extension with the body of the third lumbar vertebra as point of rotation, hip being fixed, and angle set at 0° (i.e., sitting, upright posture). Strength of hip abduction and adduction was measured with a David 310 Abduction and a David 320 Adduction, respectively, with hip joint as point of rotation, pelvis and torso being fixed, and angle of leg flexion fixed at 45°. Angle of leg abduction was set at 45° for strength measurement of adduction and 15° for abduction.

To ensure proper muscle warm-up, subjects performed several submaximal isometric efforts before the maximal tests. Strength testing consisted of two maximal contractions with 45 to 60 s rest in between. Peak strength was recorded by the David software. The highest value of the two contractions was taken as the maximal isometric strength of back extension, hip abduction, and hip adduction, respectively.

BMD was measured with dual-energy X-ray-absorptiometry (DXA) using two Hologic QDR-1000 instruments in a mobile unit as described previously (27). BMD was measured at L2–L4 of lumbar spine (LSP), at femoral neck (NECK), trochanter major (TROCH), regio intertrochanterica (INTER), and ward's triangle (WARDS).

Statistics

The mean and standard deviation (*SD*) were calculated for anthropometric data, training histories, strength parameters, and bone densities. BMD values were given as absolute values as well as percentual differences from UT. One-way analysis of variance (ANOVA) and, in case of a significant *F* ratio, Newman-Keuls post hoc test were used to compare the subjects characteristics between the groups. Pearson product-moment correlations between variables were also calculated, and their significance from zero was tested. Finally, stepwise multiple regressions, using weight, height, BMI, LBM, body fat mass, waist and hip circumferences, arm span, and grip strength to predict BMD at LSP and FEM, respectively, were performed. Statistical significance was accepted at the $p < .05$ level.

3 Results

Physical Characteristics

Most of the subjects had a dominant right arm (149 vs. 26) and a dominant left leg (97 vs. 78). ANOVA revealed a significant main effect of the subgroups in each single anthropometric variable (Table 1a–b).

Training Characteristics

ANOVA revealed significant group effects in each training parameter (Table 2). Triathletes and cyclists had more hours of weekly training compared to the other athletes.

Grip and Muscle Strength

Grip strength at the right hand was significantly higher compared to the left hand (1.33 ± 0.19 bar vs.1.30 ± 0.19 bar, $p < .05$). A relevant sport-specific effect on grip strength could not be demonstrated (Table 3). Strength values of back extension and hip abduction and adduction also showed no clear sport-specific effects. Untrained controls even had middle to high mean strength values.

Table 1a Anthropometric Characteristics

Subject	*n*	Age (years)	Weight (kg)	Height (cm)	BMI (km · m^{-2})	Body fat mass (kg)	LBM (kg)
HA	28	20.7 ± 3.4[bcg]	80.1 ± 15.6[de]	177.9 ± 9.3[b]	25.4 ± 3.6[def]	11.6 ± 4.6[cdefg]	68.8 ± 12.1
TS	25	23.2 ± 2.1[acef]	81.7 ± 7.3[de]	186.9 ± 7.1[ad]	23.4 ± 1.2[d]	11.0± 2.4[cdefg]	70.8 ± 5.7[de]
STU	44	25.5 ± 2.1[abdef]	76.5 ± 7.5[d]	182.0 ± 5.8	23.1 ± 1.7[d]	10.1 ± 2.8[abg]	66.4 ± 5.7
R	21	21.8 ± 3.4[cfg]	69.5 ± 7.0[abcfg]	180.3 ± 8.2[b]	21.3 ± 0.9[abcg]	7.9 ± 1.8[abg]	61.6 ± 5.8[b]
TRI	18	20.6 ± 3.6[bcg]	72.6 ± 5.5	181.9 ± 5.0	21.9 ± 1.5[ag]	8.2 ± 2.3[abg]	64.4 ± 3.6[b]
C	12	19.4 ± 3.6[bcdg]	77.0 ± 9.7[d]	183.4 ± 7.5	22.8 ± 1.7[a]	10.0 ± 2.6[abg]	67.0 ± 7.2
UT	25	25.5 ± 2.4[adef]	80.0 ± 10.9[d]	182.5 ± 6.0	24.0 ± 2.8[de]	13.2 ± 4.3[abcdef]	66.8 ± 7.1

Note. Values are means ± 1 *SD*. HA: heavy athletics; TS: team sport athletes; STU: trained sport students; R: running; TRI: triathlon; C: cycling; UT: untrained controls (UT). [a]Significantly different from HA; [b]significantly different from TS; [c]significantly different from STU; [d]significantly different from R; [e]significantly different from TRI; [f]significantly different from C; [g]significantly different from UT.

Table 1b Anthropometric Characteristics

Subject	*n*	Arm span (cm)	Hip (cm)	Waist (cm)	Hip · Waist^{-1}
HA	28	181.3 ± 9.6[b]	96.8 ± 7.8	81.1 ± 9.1	1.20 ± 0.06
TS	25	191.3 ± 7.2[acdefg]	96.7 ± 5.1	80.7 ± 3.9	1.20 ± 0.07
STU	44	185.5 ± 6.2[b]	94.5 ± 5.2	79.6 ± 5.6	1.19 ± 0.05
R	21	182.4 ± 8.5[b]	91.6 ± 5.6[g]	76.2 ± 3.7[g]	1.20 ± 0.04
TRI	18	184.8 ± 6.1[b]	92.7 ± 4.1[g]	77.0 ± 4.6[g]	1.21 ± 0.04
C	12	185.8 ± 7.2[b]	95.2 ± 6.7	77.8 ± 6.6[g]	1.23 ± 0.07[g]
UT	25	185.5 ± 6.9[b]	98.4 ± 5.6[de]	84.6 ± 8.4[def]	1.17 ± 0.08[f]

Note. Values are means ± 1 *SD*. See Table 1a for key to abbreviations. [a]Significantly different from HA; [b]significantly different from TS; [c]significantly different from STU; [d]significantly different from R; [e]significantly different from TRI; [f]significantly different from C; [g]significantly different from UT.

Table 2 Training Characteristics of the Athletes

Subject	*n*	Training sessions per week	Duration of training per week (hours)	Duration of training in the actual sport (years)
HA	28	6.6 ± 2.7[ce]	10.9 ± 3.7[de]	4.9 ± 3.6
TS	25	5.5 ± 1.4[def]	10.9 ± 2.5[de]	6.5 ± 4.5
STU	44	4.5 ± 2.2[adef]	9.0 ± 5.6[de]	2.6 ± 2.2[d]
R	21	7.7 ± 1.7[be]	12.7 ± 4.7[de]	3.4 ± 2.1[c]
TRI	18	12.3 ± 3.7[abdf]	18.5 ± 5.3[abcd]	3.4 ± 2.6
C	12	7.6 ± 3.2[be]	18.3 ± 8.6[abcd]	4.0 ± 2.1

Note. Values are means ± 1 *SD*. See Table 1a for key to abbreviations. [a]Significantly different from HA; [b]significantly different from TS; [c]significantly different from STU; [d]significantly different from R; [e]significantly different from TRI; [f]significantly different from C.

Table 3 Strength of Athletes and Untrained Controls

Subject	*n*	Grip strength right hand (bar)	Grip strength left hand (bar)	*n*	Back extension (Nm)	Hip abduction (Nm)	Hip adduction (Nm)
HA	28	1.24 ± 0.24	1.25 ± 0.24	6	425 ± 117	348 ± 45[de]	489 ± 101
TS	25	1.36 ± 0.17	1.33 ± 0.17	12	429 ± 150[d]	353 ± 41	473 ± 100
STU	44	1.39 ± 0.15[d]	1.34 ± 0.18	24	353 ± 79	328 ± 65	416 ± 98
R	21	1.22 ± 0.17[c]	1.19 ± 0.15	7	255 ± 50[bg]	284 ± 61[a]	360 ± 56
TRI	18	1.37 ± 0.11	1.30 ± 0.15	5	323 ± 49	289 ± 51[a]	390 ± 77
C	12	1.35 ± 0.23	1.35 ± 0.23	0			
UT	25	1.32 ± 0.20	1.29 ± 0.16	6	376 ±146[d]	387 ± 92	435 ± 103

Note. Values are means ± 1 *SD*. See Table 1a for key to abbreviations. [a]Significantly different from HA; [b]significantly different from TS; [c]significantly different from STU; [d]significantly different from R; [e]significantly different from TRI; [f]significantly different from C; [g]significantly different from UT.

Bone Mineral Density

At most sites, BMD was highest in heavy athletes, followed by athletes in team sports and sport students, and lowest in cyclists and untrained controls (Table 4a–b). At lumbar spine two main groups of sport could be established according to significant inter-group differences in their BMD. Highest BMD values could be detected in heavy athletes, team sport, and sport students, all of them having significantly higher values compared to runners, triathletes, cyclists, and untrained controls. Furthermore, BMD in heavy athletes was significantly higher compared to sport students. At femoral regions, inter-group differences of absolute BMD values were more gradual, with the highest values again in heavy athletes, team sport, and sport students, followed by runners and triathletes, with the cyclists and untrained controls showing the lowest values.

Table 4a BMD at LSP in Athletes and Untrained Controls

Subject	*n*	BMD LSP ($g \cdot cm^{-2}$)
HA	28	1.36 ± 0.17[cdefg]
TS	25	1.28 ± 0.14[defg]
STU	44	1.22 ± 0.13[adefg]
R	21	1.10 ± 0.13[abc]
TRI	18	1.08 ± 0.09[abc]
C	12	1.09 ± 0.11[abc]
UT	25	1.09 ± 0.14[abc]

Note. Values are means ± 1 *SD*. See Table 1a for key to abbreviations. [a]Significantly different from HA; [b]significantly different from TS; [c]significantly different from STU; [d]significantly different from R; [e]significantly different from TRI; [f]significantly different from C; [g]significantly different from UT.

Table 4b BMD at Femoral Sites in Athletes and Untrained Controls

Subject	n	BMD NECK ($g \cdot cm^{-2}$)	BMD TROCH ($g \cdot cm^{-2}$)	BMD INTER ($g \cdot cm^{-2}$)	BMD WARDS ($g \cdot cm^{-2}$)
HA	28	1.21 ± 0.17[cdefg]	1.01 ± 0.13[defg]	1.43 ± 0.16[efg]	1.10 ± 0.19[cdefg]
TS	25	1.17 ± 0.15[cdefg]	1.01 ± 0.13[defg]	1.46 ± 0.16[efg]	1.04 ± 0.15[fg]
STU	44	1.08 ± 0.15[abfg]	0.96 ± 0.14[fg]	1.37 ± 0.18[fg]	0.95 ± 0.17[g]
R	21	1.05 ± 0.13[abfg]	0.91 ± 0.12[abg]	1.36 ± 0.16[fg]	0.93 ± 0.13[g]
TRI	18	1.03 ± 0.11[abfg]	0.88 ± 0.09[ab]	1.31 ± 0.12[ab]	0.92 ± 0.13[g]
C	12	0.95 ± 0.13[abcde]	0.84 ± 0.11[abc]	1.20 ± 0.15[abcd]	0.84 ± 0.14[ab]
UT	25	0.91 ± 0.11[abcde]	0.81 ± 0.10[abcd]	1.23 ± 0.15[abcd]	0.78 ± 0.12[abcde]

Note. Values are means ± 1 *SD*. See Table 1a for key to abbreviations. [a]Significantly different from HA; [b]significantly different from TS; [c]significantly different from STU; [d]significantly different from R; [e]significantly different from TRI; [f]significantly different from C; [g]significantly different from UT.

Percentual Differences of BMD Compared to Controls

In order to better demonstrate training-specific effects on BMD at the different sites, percentual differences of BMD of the athletes from the untrained controls were calculated (Figure 1). Three main groups of athletes could be detected. In group I, consisting of heavy athletes, team sports and sport students, percentual differences from untrained controls were highest and significant at any site of the skeleton (LSP and FEM). The range was between 11.7 and 40.8%. In group II, consisting of runners and triathletes, no significant percentual differences from untrained controls at LSP could be detected (range between –1.6 and 0.5%), while differences were significant at FEM, except for triathletes at TROCH and INTER. The range at FEM was between 10.4 and 18.5%. Group III, consisting of cyclists only, showed no significant percentual differences from untrained controls at any site. The range in this group was between –2.4 and 7.1%.

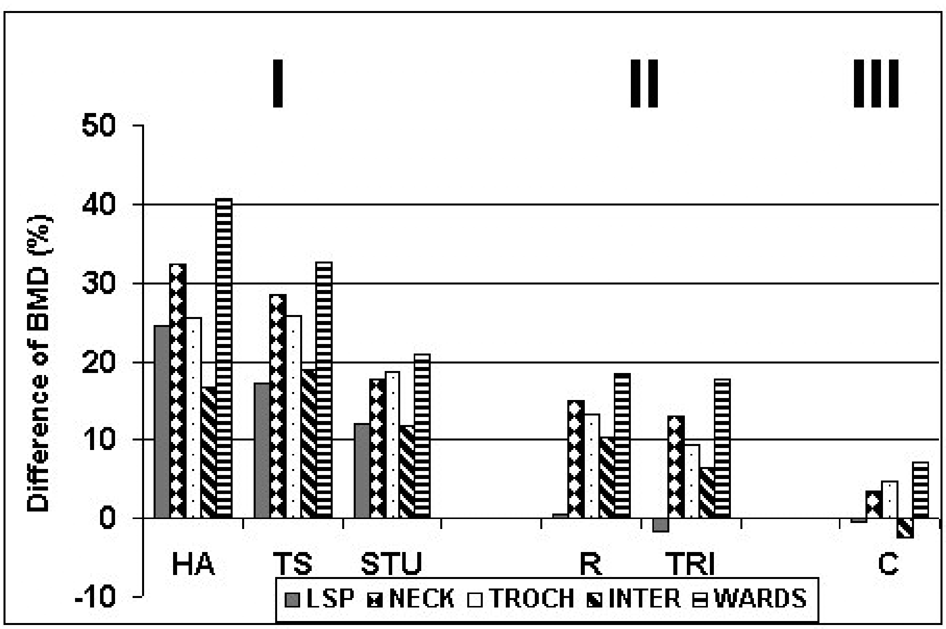

Figure 1 — Percentual differences between BMD of the single sports and those of untrained controls at LSP and femoral sites; for abbreviations see text. I: significantly higher at all sites; II: significantly higher at nearly all femoral sites but not at LSP; III: no significant differences at any site.

Table 5 Correlation Coefficients Between Anthropometric Characteristics and BMD of Athletes and Untrained Controls

Variable	LSP	NECK	TROCH	INTER	WARDS
Weight	0.44**	0.34**	0.34**	0.39**	0.23**
Height	0.23**	0.18*	0.23**	0.21**	0.10
BMI	0.40**	0.31**	0.26*	0.35**	0.22**
Hip/Waist	0.03	0.00	0.00	0.08	0.03
Arm span	0.25**	0.23**	0.27**	0.23**	0.16
Fat mass	0.15	0.00	0.00	0.14	0.07
LBM	0.47**	0.41**	0.40**	0.42**	0.30**

Note. See Table 1a for key to abbreviations. *$p < .05$; **$p < .01$.

Correlations Between Anthropometric, Training, and Strength Characteristics, and BMD

Positive significant correlations could be detected between most BMD variables and the anthropometric parameters weight, height, BMI, arm span, and LBM, while fat mass and hip/waist ratio showed no significant correlation with BMD (Table 5). Only slight correlations could be found between training characteristics and BMD at LSP. While years of training were positively correlated with BMD at LSP ($r = 0.21$, $p < .05$), number of training sessions and training hours per week correlated negatively with BMD at LSP ($r = –0.23$, $p < .01$, and $r = –0.21$, $p < .05$, respectively). BMD at FEM showed no significant correlation to any training parameter.

All strength values correlated positively with BMD at LSP (Table 6). The closest correlations could be demonstrated for strength of hip abduction and hip adduction. No parameter of muscle strength correlated with BMD at WARDS, while most strength parameters correlated slightly with BMD at the other femoral sites.

Altogether, although partly significant, correlations between anthropometric, training, and strength characteristics, and BMD, were rather weak.

Table 6 Correlation Coefficients Between Strength Characteristics and BMD of Athletes and Untrained Controls

Variable	*n*	LSP	NECK	TROCH	INTER	WARDS
Grip strength (right hand)	174	0.22**	0.12	0.17*	0.16*	0.05
Grip strength (left hand)	174	0.26**	0.19*	0.26**	0.21**	0.15
Back extension	60	0.37**	0.25	0.26*	0.22	0.25
Hip abduction	60	0.40**	0.26*	0.26*	0.32*	0.18
Hip adduction	60	0.43**	0.24	0.28*	0.22	0.21

Note. See Table 1a for key to abbreviations. *$p < .05$; **$p < .01$.

Stepwise Multiple Regression Prediction of BMD at LSP and Femoral Sites

Stepwise multiple regression prediction of BMD at LSP was analyzed from 9 variables, including height, weight, BMI, LBM, fat mass, arm span, hip/waist ratio, and left and right hand grip strength ($n = 173$). Strength of lumbar extension, hip abduction, and hip adduction was not included due to the relatively small number of cases.

From all variables LBM was selected first as predictor for BMD at LSP and height second (β = 0.73 and β = –0.29, respectively; r = 0.53). At the femoral sites, LBM was also selected first from the 9 variables (NECK: β = 0.60, TROCH: β = 1.14, INTER: β = 0.65, WARDS: β = 0.50; r = 0.46, 0.44, 0.45, and 0.37, respectively). At NECK, LBM was followed by fat mass (β = –0.29). At TROCH, LBM was followed by weight (β = –0.77). At INTER, no other variable was a significant predictor for BMD after LBM. At WARDS, fat mass was selected second after LBM (β = –0.31).

4 Discussion

Anthropometric Parameters

Due to sport-specific demands and group-specific selection, anthropometric parameters showed wide inter-group variations. Variation in age might be explained by the fact that the younger bikers, triathletes, and power athletes were selected from a regional junior athlete group. Differences in weight, BMI, LBM, height, and corresponding arm span could mainly be explained by sport-specific anthropometric profiles: In sports like running and triathlon, where body weight is a limiting factor for top results, body weight, LBM, and BMI were small. However, power athletes revealed a high BMI. This was expected as athletes in judo and wrestling most often have a strong and compact body frame and therefore a high BMI. High standard deviation in weight and LBM in the group of power athletes might be explained by selection of athletes from different weight classes. As great height is an advantage in many ball sports, like volleyball, basketball, and handball, athletes with a great height could be expected to dominate these groups. Low body fat mass is a criterion for many athletes and often creates an advantage, especially in sports where body weight must be carried or in sports with weight classes like judo and wrestling. Therefore, non-athletes could be expected to have a higher fat mass than all sport groups, while runners and triathletes the lowest values in fat mass.

Most studies on the relationships between anthropometric characteristics, bone mineral densities, and bone mass in trained and untrained males revealed positive correlations between BMD values and anthropometric characteristics (5, 6, 13, 21). Also, it has been well documented over time that missing gravitational forces, as in weightlessness and during immobilization, lead to skeletal demineralization (16, 22). As the skeleton adapts functionally, normal activities in daily life in the gravitational field of the earth have positive osteogenic effects on bone. In the present investigation, positive and significant, although weak, correlations between weight, height, BMI, arm span, and LBM on the one hand, and BMD at LSP and FEM on the other hand, could be demonstrated when analyzing the single effects. Each of these parameters has mechanical effects on bone in the gravitational field. One might therefore conclude that BMD is affected by these parameters under conditions of daily life. Stepwise multiple regression, however, only revealed positive effects on BMD for LBM, while fat mass, height, and weight even were negatively correlated to BMD at some single sites. This means that not the global but the active body mass, which is mainly determined by the muscle mass, is the most dominant positive predictor for BMD in young and healthy men.

Summarizing the anthropometric effects on bone, the passive effects of body mass or height and length parameters have only minor osteogenic effects in daily life, when no pathological conditions like weightlessness or immobilization exist. The most important factor is the lean body mass, which is mainly determined by regular training, especially when including power training. The positive effects of LBM are not explainable as simple weight effects, but as the results of the stimulatory forces of the muscles being anatomically closely connected to the bones.

Training Parameters

In the whole group of athletes, only a few significant correlations between investigated training parameters and BMD could be detected. BMD at the lumbar spine was significantly but only slightly correlated with years of training in the present sport. Hours of training were even negatively correlated with BMD at LSP. This negative correlation might be explained by group-specific effects: Cyclists and triathletes and, to a smaller extent, runners, trained much more than the other groups, but showed the lowest BMD. At femoral sites, no correlations at all could be found between training parameters and BMD.

These findings emphasize the impact of sport-specific differences on BMD and reveal that high osteogenic effects are not primarily affected by training quantity but training quality. A minimum effective strain seems to be necessary for bone formation to occur independent of training frequency (8).

Grip and Muscle Strength

Results of grip and muscle strength measurements unexpectedly revealed only slight inter-group differences. Basal grip strength is trained to a large extent by daily activities. This explains the fact that higher right hand grip strength was correlated with the dominance of the hand. In spite of missing sport-specific differences, some significant correlations with BMD values could be demonstrated. Especially BMD at LSP was clearly and positively correlated with all three strength variables. These varying results in male athletes reflect the somewhat controversial studies in females, where also more complex and not just local adaptations of BMD as a result of manifold forces were detected (15, 21, 26). The main explanation for these diverse results is that in most training regimes not only local stimuli are set, but multidimensional muscular and bony demands and stimulations also occur, especially in complex sports like ball sports, judo, and wrestling, as well as during the sport study. Furthermore, as the direct strength effects induced by the activated muscles and the pure mechanical effects when moving the body overlap, the single results become effaced, leading to only slight correlations between BMD and muscle strength. As the very clear sport-specific effects on BMD are not mirrored by sport-specific effects on strength values, we conclude that the mechanical stimulatory factors, such as high impact loading and multidimensional forces, are more important for building up a high BMD than the direct muscle-induced effects.

Bone Mineral Density

BMD values depended clearly on the kind of sport and the region of measurement. Highest values on nearly all regions were found in heavy athletes. This is reflected uniformly in the existing literature, where high values of BMD were found in athletes of power sports (6, 10, 25). In addition to these results, we also found values of BMD to be nearly as high in ball sports and, to a lesser extent, in the unspecifically but multidimensionally trained sport students. These results are in agreement with an investigation in soccer in which elevated BMD were found in regions of lower extremities and pelvis (28).

The sport- and region-specific effects that could be demonstrated for the absolute BMD values in the present investigation were even more pronounced in the percentual differences of BMD between athletes and untrained controls. These differences were significant for BMD at LSP and femoral regions in heavy athletes, team sport, and sport students (group I in Figure 1), indicating that all three sports induce high mechanical strain in these regions inducing bone formation. In contrast to this group, runners and triathletes showed no differences in their BMD at LSP compared to untrained controls, in spite of very high training volumes. Runners and triathletes, however, had significantly elevated levels in most femoral regions (group II, Figure 1). In cyclists, no significant differences at any site could be detected (group III, Figure 1). These results are in context with the available literature. Female runners had normal BMD values at LSP, but elevated values at the femoral sites (12). Female cyclists even had lower values of BMD at LSP and the femoral sites compared to moderately trained controls (11).

Explanations for these results can be given when analyzing the sport-specific loads: The strain on a bone is mainly determined by mechanical forces. Dynamic forces depend on body mass and acceleration. In judo and wrestling, movements correspond to high maximal strength and power. Besides forces induced my muscular activation, high accelerations and therefore high forces, as well as varied patterns of strain, occur when falling. Furthermore, special strength training with heavy weights is a typical and regular training method in these sports. Therefore, high bone formation can be expected in judo and wrestling. Movements in the investigated ball games induce mechanical forces on the whole body. Sport-specific movements are uncyclic and multidimensional. Demands in jumping, during short sprints, and stoppings are of very short duration, inducing very high accelerations and, therefore, strains. In middle and long distance running, dynamic loading of the whole body occurs, with the upper body having a stabilizing function and the lower extremities doing the main work of moving forward. In cycling, dynamic loading only stresses part of the body, which is mainly the lower extremities, while upper body is fixed by the arms and only stressed statically. Power is used to overcome driving resistance. Only small forces and accelerations are to be expected when cyclic and round pedaling is used.

These analyses on sport-specific demands and osteogenic effects as well as our own results in BMD differences between sports are in accordance with results of animal studies (4). In animals, new bone formation did not depend on duration of a mechanical stimulus but on its height, frequency, and repetition. Demands of high frequency and height and with an unphysiological pattern seem to be the best stimulators of bone formation. According to these studies, high strain should occur primarily in short duration, dynamic exercises with high intensities and variations in time. In the present investigation strains at lumbar spine and femoral sites are probably higher in sports of group I (HA, TS, STU) compared to group II (R, TRI) and III (C). Furthermore, exercise-induced strains at femoral sites are higher in sports of group II compared to group III.

We therefore conclude:

1. Athletes who move their whole body with high accelerations and in multidimensional directions, like in ball sports and during the sport study, as well as athletes who move with high power in a dynamic and multidimensional way, like power athletes in judo and wrestling, have high positive osteogenic effects at both sites, the lumbar spine and the femoral regions.

2. If athletes primarily use their lower extremities in a dynamic way for moving forward, and whole body has to be carried by lower extremities, like in running, positive osteogenic effects will primarily occur at the lower extremities.

3. Demands in sports like cycling—where only part of the body mass (lower extremities) is used dynamically and cyclically without high accelerations and impacts, and most of the rest of the body is carried passively sitting on the saddle and being fixed by the arms—are too low to induce a remarkable osteogenic stimulation at the axial skeleton and the proximal femur.

In the present investigation one might proceed on the assumption that high BMD values are accompanied with high bone stability. In order to induce further bone formation, mechanically induced strain needs to exceed the actual "setpoint-strain." As percentual differences between BMD values of the athletes in group I and the untrained controls at LSP were not as high as at most femoral sites, we conclude that exercise induced strain in the lumbar spine is comparably low. This might be due to the anatomical double-S structure of the spine and the buffering intervertebral disks. In an experiment with a massive model at the femur during a normal movement (period of the standing leg phase while walking), Pauwells (20) found the smallest tension at the WARD's triangle. This is the mechanical reason for the anatomically typical reduction of material at this site, leading to low BMD values at WARDS. This, however, also means that this site is not well protected against overuse during unusual demands (like falling) and, therefore, is at high risk for fracture. Interestingly, in the present investigation, highest percentual differences of BMD between athletes and untrained controls were found at WARDS for almost all sports except TRI. We therefore conclude that mechanically induced adaptations at the proximal femur occur especially at the site with the highest risk for fractures, the WARD's triangle, leading to higher BMD values and thereby, probably, to higher stability.

According to the above mentioned facts and correlations, we conclude that osteogenic effects are not sport-specific but load- and body region-specific. Height of strain is the most important factor for bone formation in male humans. Therefore, training regimes with high volume but low intensities do not or only slightly induce osteogenic effects, while a variable training protocol with short but high forces will have the highest positive stimulatory effects on bone formation.

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